TECHNICAL MEMORANDUMS

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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No. 361

METAL AIRPLANE CONSTRUCTION

Paper read at the Third International Congress of Aerial Navigation held at Brussels in October, 1925.

Washington,
May, 1926

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

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METAL AIRPLANE CONSTRUCTION.*

At the end of the war the scarcity of dry wood compelled airplane constructors to provide for its replacement by metal. Since then the advantages of metal construction have proved many and important.

Wood, in general, does not possess well-defined mechanical properties, since these vary with the density, the degree of humidity and the source of the wood. This is not true of metals, whose mechanical characteristics are more constant and easy to control. Inclement weather can diminish the strength of a piece of wood nearly two-thirds. Independently of this reduction in strength, humidity causes deformation and warping of the wings and tail group, which may impair the stability of the airplane. Even the weight of the water absorbed may be enough to affect the performances of an airplane.

It has often been noticed that ruptures of wood airplanes are more sudden and complete than those of metal airplanes. Wood splits and splinters. Metal yields and bends, thus sometimes enabling a landing, which a wooden airplane would not have time to make.

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Metal construction is better than wooden for quantity production. The cost of a specimen airplane in wood is less than in metal, but there is reason to believe that a metal airplane constructed in quantity would ultimately cost less than a wooden one of the same type, provided the former is economically designed. Aluminum alloys and steel are easily obtained, while most of the wood used in airplanes must be imported from other countries and requires long drying. It is consequently difficult to obtain, especially in time of war.

It has long been thought that metal construction of airplanes would involve an increase in weight as compared with wood construction. Recent experience has shown, however, that such is not the case and that, on the contrary, it is really lighter for medium and large commercial airplanes and even for small airplanes with a heavy wing loading. Of two airplanes (metal and wood) having the same external appearance, the metal one is the lighter.

I. Materials Used, Treatment, Characteristics.

The metals chiefly used are steel and light alloys of aluminum (of the duralumin type).

The important characteristics of metals for airplane construction are: breaking strength R; limit of elasticity E; elongations A; resilience ρ; danger limit; modulus of elasticity; density D (as small as possible).

It is especially advantageous to employ a metal in which the rupture limit exceeds the elasticity limit as much as possible. One can be warned of the imminence of rupture by the appearance of permanent deformations and may thus avoid a serious accident. This is true, however, only when the rupture occurs in parts subjected to tensile or bending stresses. When the rupture is produced by compression (buckling) it is generally sudden. The importance which may be assumed by the modulus of elasticity is immediately obvious, since this comes into the calculations of compressed parts. We shall have occasion to recur to this point. From another viewpoint, it is manifestly important to select a metal for which R/D is as great as possible.

The danger limit (the upper limit of resistance to stresses indefinitely repeated) is one of the most important characteristics. It is particularly important in the framework of an airplane, which is necessarily subjected to vibrations. It seems, indeed, as the result of numerous investigations, that the vibrations and the alternate stresses ultimately overcome the resistance of a part and start slight cracks which gradually increase. Wöhler's experiments seem to prove that rupture can occur as the result of stresses not exceeding one-half the limit of elasticity. Mr. Fremont, director of the laboratory of mechanics at the School of Mines, thinks that the interpretation of these experiments rests on an inadmissible hypothesis and that we cannot consider the stress of the most fatigued fiber as balancing the static stress it would have to withstand at each alternation. It seems as if there were reason to consider that in reality a part can resist the alternate stresses indefinitely, when the limit of elasticity is not reached at any point, and that, in the contrary event, it is the unrestored work that, by accumulating, ultimately causes permanent deformation. In support of his hypothesis, Mr. Fremont has demonstrated that it is not by increasing the size of the part, but, on the contrary, by removing the metal at certain judiciously chosen points, that the elasticity of the part is increased and that it is enabled to eliminate a greater quantity of the dynamic work. Such indications are obviously valuable in aeronautics, since they enable the conciliation of lightness with strength.

It follows, however, from these experiments, that it is important to avoid all cold working or poor thermal treatment susceptible of producing permanent distortions which may lead to accidents or premature ruptures. We must therefore distrust cold-worked parts and always subject them to a tempering process, in order to restore them to their normal state before using them.

a) Light aluminum alloys.- These always contain copper (3-4%), magnesium (0.5%), manganese (0.5-1%); sometimes zinc

(1.5 - 3%), iron and silicon in very small quantities, the importance of which is, however, far from being negligible.

The two best known alloys in France are duralumin and "alferium," whose mechanical characteristics are practically the same. The minimum qualifications imposed by the French official specifications are: breaking strength $R = 35$ kg/mm² (49782 lb./sq.in.); limit of elasticity $E = 22$ kg/mm² (31292 lb./sq.in.); elongation $A = 20$.

The effects of cold working, of the hardening temperatures, of the cooling speeds, of the tempering temperatures, and of the periods of rest after hardening have been investigated by different experimenters and in particular by Colonel Grard. The curves in Figs. 2-3 give the results of these researches. In Fig. 2 the variations in the mechanical properties of duralumin are plotted against the tempering temperatures and in Fig. 3, against the time elapsed after hardening at 475°C (887°F). On the other hand, the tables given below show the importance of the thermal treatments to which these metals are ordinarily subjected, namely: heating to 350°C (662°F) followed by slow cooling, in order to give them the maximum ductility and facilitate their working; heating to 475°C (887°F) and then hardening in cold water, in order to give them the maximum strength, elasticity and elongation.

1. Heated to 350°C (662°F).

Mechanical properties	R	E	A	ρ
Cooled very slowly	20	6	20	6
Cooled in still air	20	7	20	4-5
Cooled in water	20	9	15	3

2. Heated to 475°C (887°F).

Mechanical properties	R	E	A	ρ
Cooled very slowly	28	12	16	4
Cooled in still air	32	18	18	4
Cooled in water	40	20	20	4

Quite recent experiments on the resistivity of duralumin in terms of the temperature have demonstrated the important role played by the presence of silicon and magnesium, even in very small proportions. A theory of the hardening of duralumin has even been based on their influences, according to which the state of equilibrium at 475°C (887°F) is a solid solution of $mg_2\ Si$ in a solution of $Al_2\ Cu$ in the aluminum. This solid solution is transformed by cooling into a harder solid solution, but as much more slowly as the tempering temperature is lower. This explains why the tempering at the ordinary temperature is continued several days after the cooling. The effect of heating is to separate the compound $Mg_2\ Si$ mechanically which results in the formation of a softer and weaker alloy.

This seasoning effect can be utilized in a very interesting way, in many instances, for working the metal. It is, in fact, easy to work the metal immediately after quenching. This principle applies particularly to the making and setting of rivets. The rivets are set within an hour after they are quenched, while they are still sufficiently malleable to allow heading without excessive hammering. They are then left to harden and finally acquire a strength practically equal to that of the parts assembled by them.

These alloys oxidize and lose their luster in moist air, because of the coat of alumina which covers them. This coat is very thin, however, and protects the metal underneath it from further oxidation. Although opinions are much divided on this subject, sea water seems to attack aluminum in the course of time, so that it cannot be used without risk or without special precautions in the construction of seaplanes. The present problem is to discover some paint entirely unaffected by sea water and sufficiently strong not to be disintegrated by the inevitable friction and also sufficiently adherent and elastic to follow all the distortions of the metal without tearing.

These alloys have a specific gravity of 2.8 - 2.9 and the ratio R/D = 140. They form parts lighter than wood for resisting bending or compressive stresses. These parts are in fact much lighter than indicated by the simple consideration of the ratio R/D, because they enable, for sections of given dimensions, thinner parts and consequently greater inertias and, ultimately, a relatively small surface area. Thus a piece of plain ash, having a cross section 50 × 100 mm (1.97 × 3.94 in.), develops a resisting moment which, by applying the formula RI/V to the data already indicated, is found to be of the order of 825 kgm (554.4 ft.-lb.). The same moment of resistance could be developed by a hollow duralumin girder, with flanges not over 4.5 mm (0.177 in.) thick and webs not over 1.5 mm (0.059 in.) thick and having the same outside dimensions. Since the weight is proportional to s/D, it is obvious that, in the first case, it is proportional to 37.5 and in the second case to 19, or only about one-half as much.

Certain experiments seem to indicate that the danger limit of duralumin may be quite small, of the order of about 9 kg/mm^2 (12801 lb./sq.in.) according to some investigators. It does not seem to us, however, that the experiments thus far performed are very conclusive.

It still remains for us to speak of the ultra-light magnesium alloys and alloys of aluminum and silicon. The former have a specific gravity of not over 2 and, after suitable treatment, seem to possess very important mechanical characteristics. The latter have remarkable properties, which enable their extensive use for all cast parts. One of these alloys ("Alpax") is already being manufactured. It has the following characteristics: R = 20, E = 11, A = 9%, D = 2.6.

b) Steel.- This has been used from the first in aeronautic construction, in the assembling pieces, the rods and axles of the landing gear, in the form of soft-steel tubes assembled by autogenous welding. The properties of resilience and hardness vary inversely as the content in carbon. This content and the suitable thermal treatment are therefore determined by the proposed conditions of utilization.

Steel is, however, not generally suitable for the framework itself; unless, perhaps, it is not feared to employ autogenous welding for assembling soft-steel tubes, as is done by the Fokker Company. The lightness of this union makes it possible to accept a slight excess in weight due to the low breaking strength of the steel employed. For all tubes of small l/r (l = length of buckling, ρ = radius of gyration), the resistance to buckling depends especially on the coefficient of elasticity, which varies but slightly for different steels.

Generally, however, it is necessary to resort to high-resistance steels, which are obtainable only in the form of special steels. In England, however, strips of carbon steel have been produced by ingenious methods of rolling and successive tempering, which are capable of immediate utilization in the form of box girders.

We have seen that aluminum alloys (which are superior to wood in this respect) have a ratio R/D of the order of 140. In order to have the same conditions of lightness, it is necessary with a steel of 7.8 specific gravity to have strengths of the order of 110 kg/mm² (156459 lb./sq.in.), a figure actually attained and even exceeded by certain special steels, which nevertheless retain a sufficient elongation and resilience. Aside from their mechanical characteristics, steels differ with respect to their use, in their ease of working, availability and cost. Since they are very hard, they need to be softened for working and then rehardened and tempered to develop their best qualities. The thermal treatments, to which they must be subjected, are more difficult than for the light alloys, due to the higher temperatures.

For small parts (assemblage pieces, connections, caps, axles, ball-and-socket joints, etc.), it seems better to employ nickel-chromium steels, with about 2.5% Ni, tempered in oil. The importance of these steels is due to the fact that, while having very high-breaking strengths - 100 kg/mm² (142235 lb./sq.in.) and more - they can be readily worked in the annealed state. Suitable tempering makes it possible to obtain very high degrees of hardness in parts subjected to wear or to obtain great resilience in parts subjected to vibrations from alternating stresses or shocks.

However, due to their tempering in oil, these steels are not adapted to the manufacture of large parts, which may deform after tempering and not be susceptible of assembling. In order to avoid this disadvantage, it is necessary to use steels which, while having the same mechanical properties, are susceptible of being tempered in the air (self-tempering steels). By way of example, we are adding (Fig. 4) the characteristic curves of a nickel-chromium-molybdenum steel tempered in air at 950°C (1742°F) in terms of the tempering temperatures (Holzer steels, mark CN 12).

It should not be concluded from our comparison of the light alloys with wood, that the special steels are much superior to the light aluminum alloys. In fact, the reverse is more often true. By simply substituting steel for duralumin, while retaining the present forms of construction, we generally arrive at thicknesses which are too thin for practical use. We will return to this subject and will indicate the repercussion which the employment of steel must have on the very conception of airplanes.

Certain steels with a large proportion of chromium are inoxidizable, which makes them very important in seaplane construction. Suitable thermal treatment gives them the following characteristics: $R = 60$, $E = 40$, $A = 20$. In particular, their great elongation renders them especially suitable for hulls and floats, where elasticity is indispensable.

Before leaving the subject of steel, it is necessary to clarify one point which has already been the object of controversies. Some writers have claimed that, in compressed parts, special steel has no great advantage over ordinary steel, basing this view on the theoretical consideration of Euler's formula, in which, for the same inertia, the resistance to buckling is proportional to the coefficient of elasticity which, as we have already stated, varies but little for different steels. In reality, Euler's formula ceases to be applicable for values of l/r below 110. For the sake of lightness, we must make compressed parts in aircraft work at values of l/r well below this figure. In this case, just as has been demonstrated by numerous experiments and in particular by the compression curve of streamlined duralumin struts, the curve of the fatigues diverges from Euler's curve and, when l/r tends toward zero, reaches values very near the breaking limit. This value therefore plays quite an important role and in practice the advantage of the special steels holds good for compression, as well as for bending and tension.

II. Principles and Methods of Construction.

The present principles are rather numerous and often conflict on the same airplane. In the actual state of the question, it is very important to discern, analyze and compare the various directive principles.

First method.- This consists in starting with materials already prepared (round and rectangular tubes, streamlined tubes and variously shaped sections, such as I, U, etc.) and in using them just as they come from the factory. The structural plan corresponding to this method is that of lattice girders, whose elements work primarily in tension or compression. The difficulty consists in determining the secondary bending stresses in the assemblies and in the flanges. This method can be applied in two ways, according to whether the plan is to use tubes or sections which are accessible on both surfaces.

a) Tubular construction involves complicated assemblies, generally consisting of pressed parts joined by tubular rivets or by swaged pieces and in certain cases by ball-and-socket joints. In any case, a considerable set of tools is required. On the other hand, this construction is, at least theoretically, very light, since a tube represents the maximum inertia for a given cross section.

b) Construction by means of simple shapes comprises, on the contrary, assemblies easily made by gussets riveted to the sides of the U's or other shapes. Such assemblies are heavy, however. On the other hand, the inertia of the shapes employed is always small, at least in certain planes. For both these reasons, this type of construction is rather heavy.

In both cases, whether involving tubes or shapes, it may be observed that this method has the disadvantage of being opposed in practice to all standardization of the production. One is automatically led to require considerable variety in the dimensions of the tubes or shapes.

The advocates of this method claim that it has the advantage of being "homogeneous." We think it gives this word a rather narrow meaning to apply it to structures made of a single material, a species of light alloy. We will see further along that real homogeneity consists in the adaptation of the material, its thickness and its forms to the exact stress it is required to withstand.

<u>Second method</u>.- This consists in using the sheet metal in large pieces, in box girders formed by long strips, suitably perforated and braced by light wires. It is derived from forms long utilized in ordinary metal construction. In our opinion, it is much more flexible. It can be much better adapted to each case and can give greater continuity than the first method. Judiciously applied, it does not require a very large set of tools. Its chief advantage, however, is its better adaptation for covering the wings with sheet metal, thereby increasing their strength.

This matter is important, because covering with fabric requires great care in order to avoid diminishing the efficiency of the wings. The conditions of any future war will oblige the airplanes to go without shelter for long periods after the preliminary destruction of the fixed organizations and the aviation bases of the enemy. Many attempts have therefore been made in this direction.

We were satisfied at first with replacing the wing fabric by thin sheets of duralumin, without changing the wing structure itself. This considerably increased the weight, because it is not practicable for this purpose to use metal sheets less than 0.4 mm (0.016 in.) thick. It is difficult to attach sheet metal of this thickness to ribs not specially prepared for the purpose. On the other hand, it is necessary to stiffen the thin metal and support it by interior spars and ribs. It was doubted whether such a system was really practicable. This led to the idea that it would be better to stretch the sheet metal over a close, continuous frame made up of an assembly of spars inclined to one another and having, in pairs, a common rib. Such a framework would strongly resist all kinds of stresses applied to the wing and the covering could be attached to it in such a way as to increase its strength. This seems to be the most recent trend of this method of construction. Another advantage of this mode of construction is to enable an airplane in combat to suffer quite severe injuries to its wings without complete rupture.

The pieces employed in the construction of airplanes, in order to be light, must be thin and also have large moments of inertia. They can be thinner in proportion as the mechanical properties of the metal employed are better. The secondary deformations resulting from lack of sufficient rigidity are here quite important and can even cause the sudden rupture of the whole wing. They necessitate special tests, since the customary formulas for the strength of materials cannot be applied here without precautions.

It is sought to obtain, without increasing the weight and without complicated treatment, a sufficient rigidity of form to prevent local deformation, by embossing, by giving a suitable shape to the sheet-metal parts, and by perforations enabling the use of thicker metal for the same weight. The perfecting of such a system is difficult.

Moreover, the employment of thin sheets raises another kind of difficulty, the tolerances in the thicknesses of the sheets being uniformly 0.1 mm (0.004 in.) for sheets 0.4 - 1 mm (0.016 - 0.039 in.) thick. This may cause variations in the weight of the framework and consequent errors in the centering.

From the safety viewpoint, slight differences in execution and slight defects in manufacture may cause considerable variation in the mechanical strength of the finished parts, sometimes amounting to 30%. This occurs especially in the riveting, due to the tendency to crush the metal under the rivet head, an injury which may be overlooked even by a careful inspector.

For all these reasons, we consider it necessary to use each material according to the purpose for which it is intended. With greater thicknesses, the overhang can be greater, the struts and lattices farther apart and the wing loading greater.

We are, moreover, limited in this direction, because excessive thicknesses give too small moments of inertia and excessive radii of curvature in bending. Some of the difficulties are then experienced which have been already mentioned for assemblies of tubes. Furthermore, flaws are difficult to detect in thick metal.

It is therefore our conviction that the thickness of the metal employed should be varied only within rather narrow limits. We are naturally led to recommend, first, the employment of duralumin, then to replace it by steel as soon as thicknesses of 5 - 6 mm (0.197 - 0.236 in.) are reached for duralumin.

Mixed construction, which has its detractors, thus logically follows. It simply imposes a few precautions regarding certain actions of contact and inequalities of expansion. We do not think, however, that these justify the criticisms of which they have been the object, nor the fears they have inspired.

Before concluding, we will say a word on the question of repairs. Though quite easy on a wooden airplane, they are more difficult in metal construction and this is another criticism which has been made of the latter. We are of the opinion that much can be accomplished in this respect by standardizing most of the parts, which would also lower their cost. It is of prime importance in designing an airplane to provide for the possibility of repairs.

The preceding considerations enable us to establish a few simple principles, which are requisite for rendering metal airplane construction practical and economical from the commercial viewpoint. It seems necessary to abandon completely the building of metal airplanes on the structural plan of wooden airplanes. We would thus arrive at difficult methods of construction requiring a large outfit of tools and consequently condemned in advance, aside from the exceptional case of production in very large quantities.

This process of development occurs in all building (edifices, bridges, etc.) in which human industry, at first restricted to wood, is finally emancipated by the more reliable and ultimately more economical use of metal.

We will conclude by saying that the mechanical properties of metals render it possible to return to the monoplanes (the conception of nature herself in the wings of birds), which is far superior from the viewpoint of aerodynamic efficiency and in which a logical use of the mechanical properties of various metals enables the elimination of external struts and the employment of large cantilever spans.

Translation by Dwight M. Miner,
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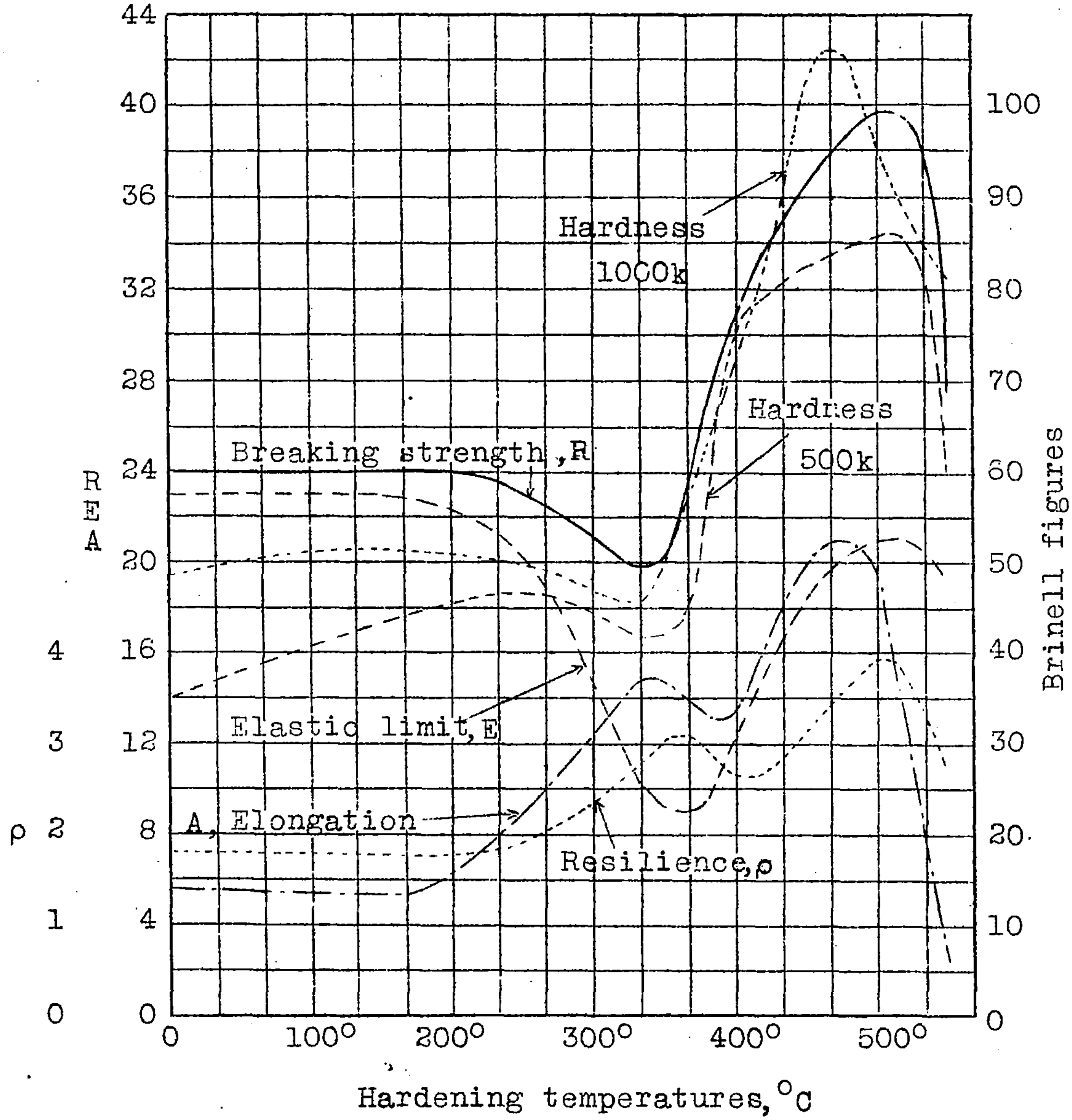

Fig.1 Variations in the mechanical properties of Duralumin plotted against the temperatures of hardening.

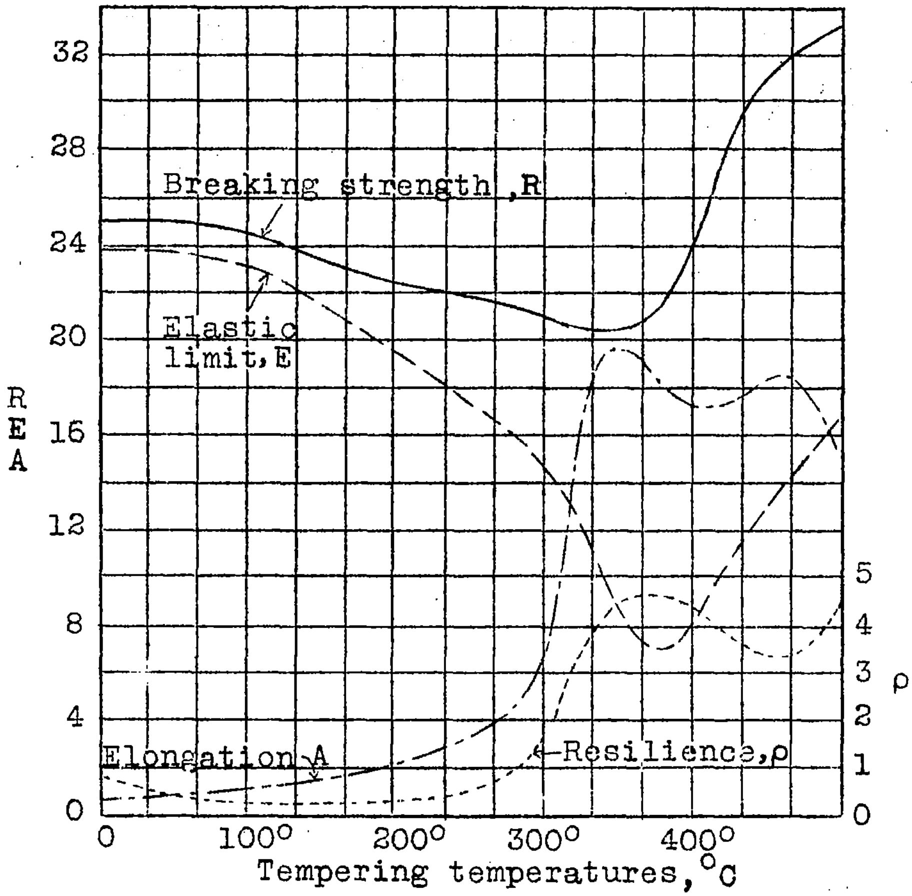

Fig.2 Variation in the mechanical properties of Duralumin plotted against the tempering temperatures.

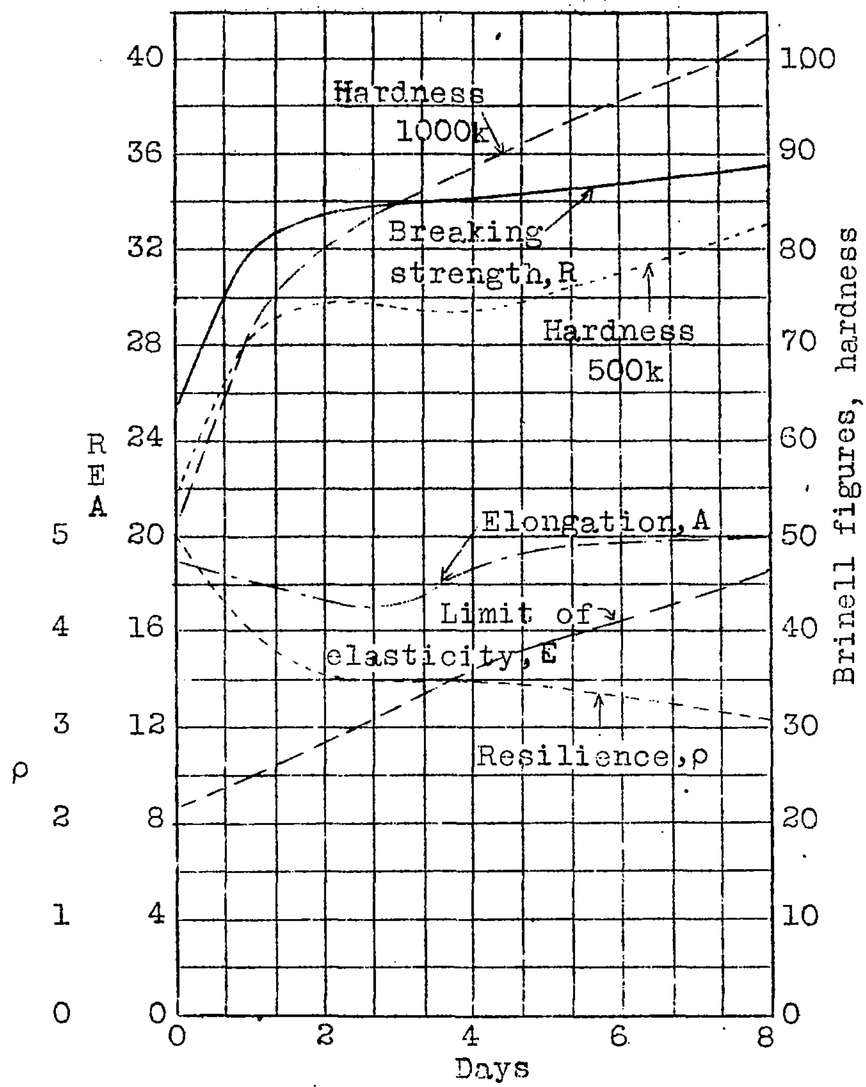

Fig.3 Variations in the mechanical properties of Duralumin plotted against the time elapsed after hardening at 475°C.

The under-lined figures indicate the Brinell imprints

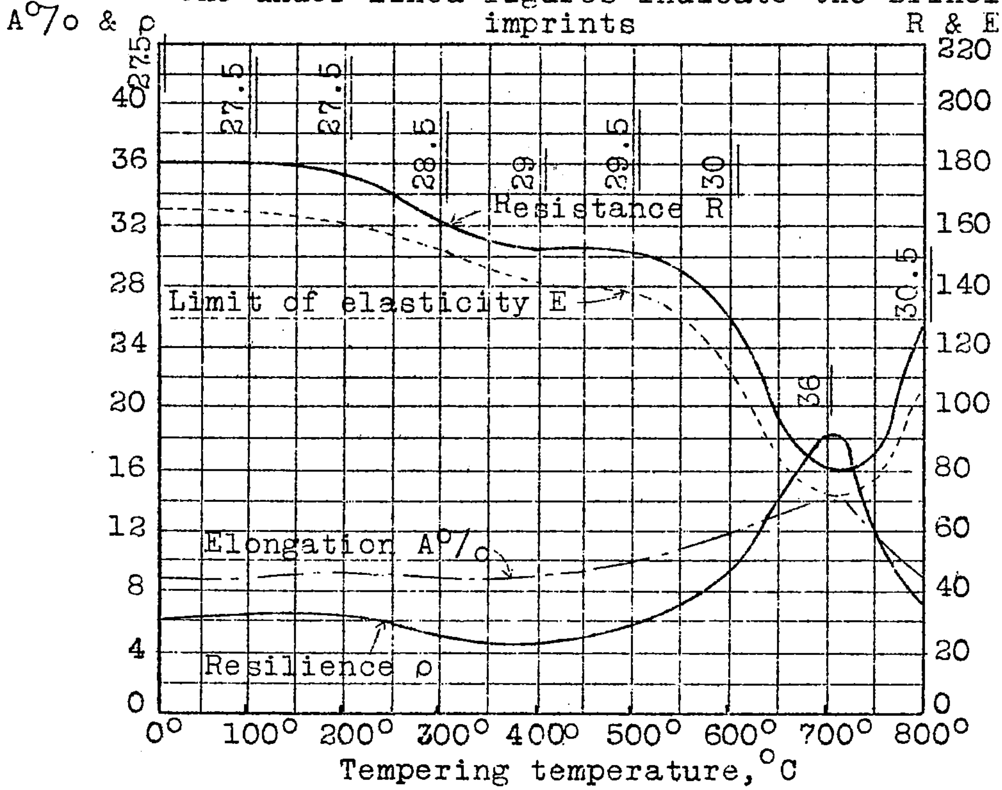

Fig.4 Holtzer steel CN 12, hardened in air at 950°C. Variation of mechanical characteristics plotted against the tempering temperatures.

Examples of assemblies.

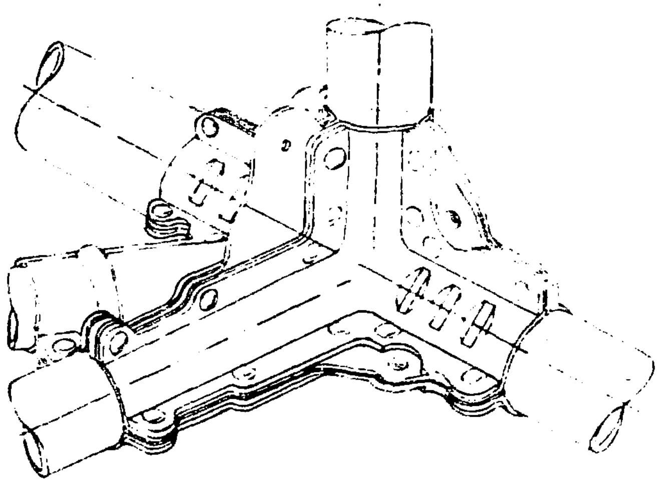

Fig.5 S.E.C.M. assembly by stamped pieces.

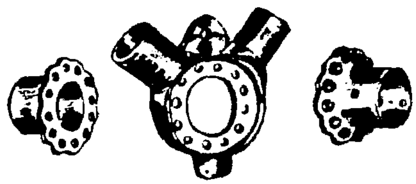

Fig.6 Breguet assembly by swaged pieces.

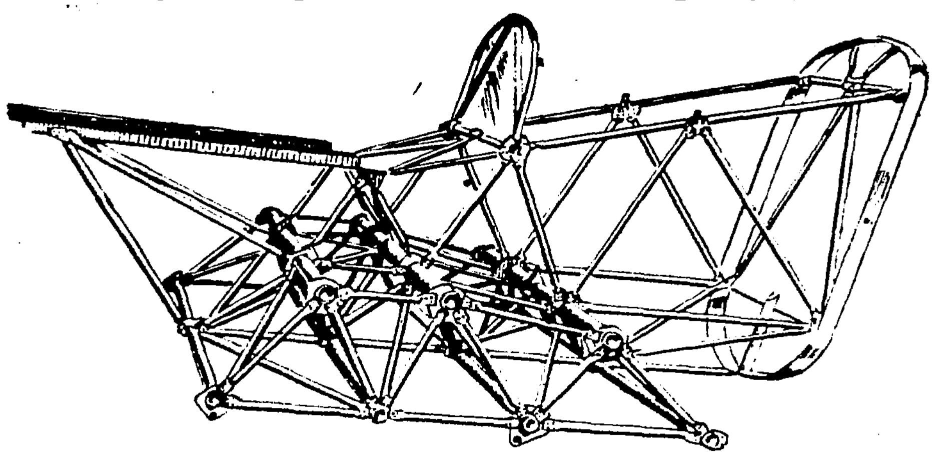

Fig.7 Tubular assembly (Junkers).

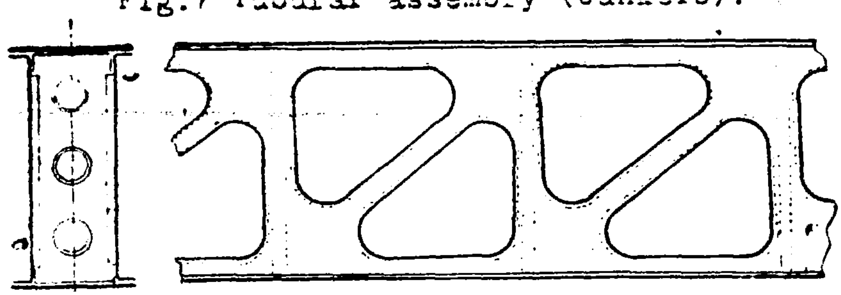

Fig.8 Open-work steel box-spar (Dyle & Bacalan airplane).

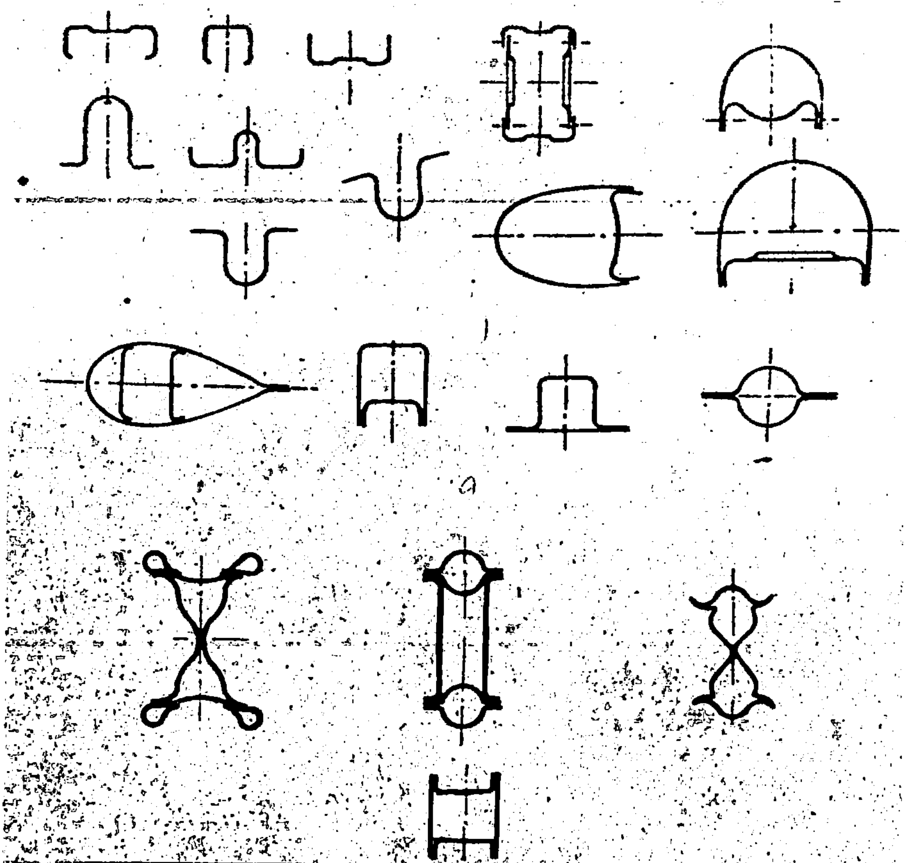

Fig.9 Various structural sections (Dornier, British, Dyle and Bacalan).

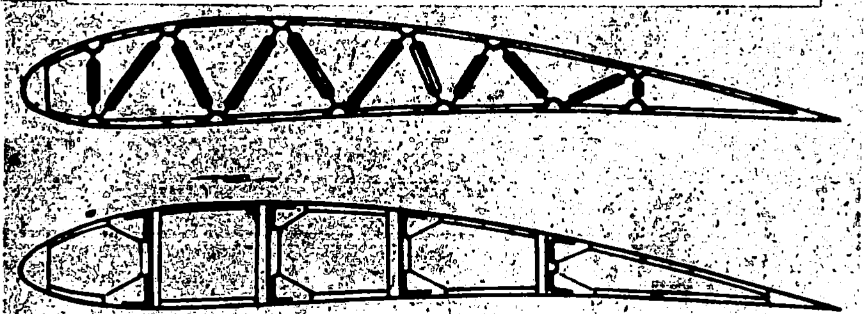

Fig.11 Wings with multiple spars (Dyle & Bacalan).

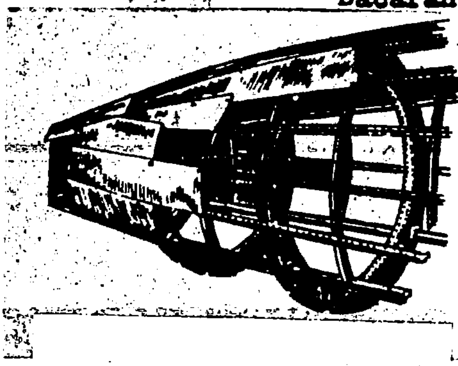

Fig.10 Example of shell structure.

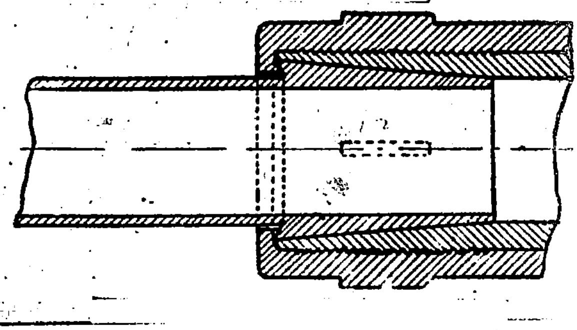

Fig.12 Conical-joint assembly (Dyle & Bacalan).